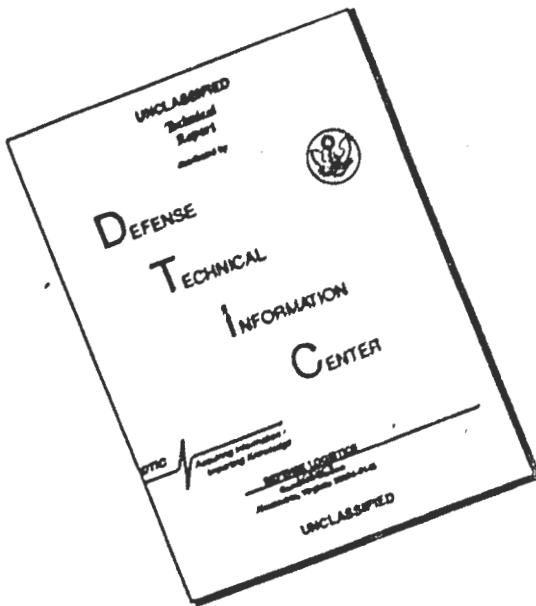


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TECHNICAL REPORT

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**SURVEY OF TRACING AND SENSING SYSTEMS
FOR THE DETAILED STUDY OF FIBROUS
MATERIALS UNDER TENSILE-IMPACT LOADING**

by

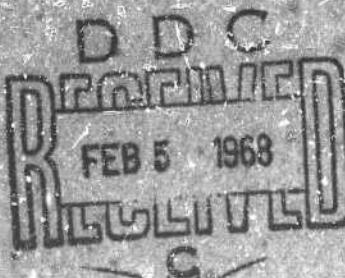
Bernard Rosen and Ross H. Supnik

Plas-Tech Equipment Corporation

Natick, Massachusetts

Contract No. DAAG17-67-C-0167

November 1967



UNITED STATES ARMY
CLOTHING AND ORGANIC MATERIALS
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TECHNICAL REPORT

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**SURVEY OF TRACING AND SENSING SYSTEMS
FOR THE DETAILED STUDY OF FIBROUS MATERIALS
UNDER TENSILE-IMPACT LOADING**

by

**Bernard Rosen and Ross H. Supnik
Plas-Tech Equipment Corporation**

Contract No. DAAG 17-67-C-0167

**Project Reference:
1L0-13001AT1A**

Series: TS-155

November 1967

**Clothing and Organic Materials Laboratory
U.S. ARMY NATICK LABORATORIES
Natick, Massachusetts, 01760**

FOREWORD

Because of a unique combination of favorable characteristics, textile fibers are used in a number of high-performance applications such as parachutes and related airdrop and safety systems. The useful forms of these materials are structured by plying and interlacing the basic yarns to provide necessary integrity, shape and physical characteristics. The technology for these structures has been developed under engineering concepts which, though reasonably substantiated by conventional test parameters, have proved unreliable and unpredictable in consideration of performance under impact.

With the development of dynamic evaluation systems such as the QMC High-Speed Impact Tester, it has been found that some of these materials respond erratically at different loading rates, and with considerably less impact strength efficiency than would be predicted from the characteristics of the fiber and yarn elements. It is believed that the differences relate to the nature and degrees of deformation and repositioning of the components within the structure. To meet new requirements for capability and reliability, it has become important to learn more of the internal mechanics of the materials under impact loadings to develop design principles specifically for dynamic applications.

The difficulties encountered during experiments for determining component responses are formidable because of the scales, speeds and extensibilities involved. While the initial in-house effort was directed to the more obvious photographic techniques for externally evidenced deformation and motion, it was desired to supplement the project by searching and reviewing other systems which might be adapted to the purpose.

This survey and screening project was initiated in June 1967 under Contract No. DAAG17-67-C-0167. The contract was administered under the direction of the Clothing and Organic Materials Laboratory, U.S. Army Natick Laboratories, with Mr. Richard D. Wells as Project Officer and Mr. Frank Figucia, Jr., as alternate.

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ABSTRACT

A survey was made of prospective tracing and sensing systems which might be applicable to investigations of component and structural deformations within fibrous materials in response to impact tensioning. The candidate systems were generally characterized and compared as to basic suitability and probable adaptability to studies of fabrics, cords, and webbings with 20 - 40% extensibility and under extension rates up to 10,000% per second. Among the more favorably considered were those using magnetic tapes, optical trackers, capacitance transducers, magnetic proximity devices, direct multiflash and high-speed photography, and photography of moiré pattern fringes, color of liquid crystals, and radiation and infrared images. Most other systems appeared either inherently, or in their present stages of development, to less well satisfy criteria of reliability, clarity of interpretation, low inertial loading, low restraint on the material, rapid response, and facility for simultaneous sensing of several key deformational factors.

Specific recommendations are made for obtaining different evidences and perspectives of events leading up to rupture of the fibrous materials, e.g., optical mapping (high-speed framing photography), thermal mapping (dynamic infrared imaging), shear-rate mapping (dynamic imaging of colored liquid-crystalline coatings), and sound mapping (dynamic 2-dimensional acoustical analysis).

SURVEY OF TRACING AND SENSING SYSTEMS FOR THE DETAILED STUDY OF FIBROUS MATERIALS UNDER TENSILE-IMPACT LOADING

1. Introduction

The increasing and widespread use of fibrous materials as components in structures that are expected to perform satisfactorily under high-speed stressing has more clearly defined the need for detailed information on the mechanisms of their deformation and failure. Such information, for example, may provide the reason why parachute suspension lines (constructed from viscoelastic nylon fibers) frequently appear weaker (1), not stronger, at higher speeds of tensing; or what specific results can be attributed to geometric-design factors in a complexly woven, or plied, fibrous material during high rates of extension.

Since this survey is conducted on an interim plane and in abbreviated form, the resolution of such complex problems can only be met by continued investigation. These two conditions cited above are to further emphasize the importance of activated research in this area.

The task here is directed to a preliminary inquiry which may currently or eventually provide useful tools for investigators entering this field of study. Several guidelines are proposed and presented below. Adequate boundaries are established.

This report provides data on initial screening and recommendations on tracing and sensing systems applicable to studies of deformations on components and structures within fibrous materials in response to impact loadings in tension.

A focus is to be placed on fabrics, webbings, and cordage such as those used in air delivery safety systems. These items are made of continuous filament (primarily nylon) yarns in various plies and in woven or braided constructions, with extensibilities in the 20 - 40% range. Extension rates up to 10,000% per second are to be included. Factors to be treated are linear strain levels and distributions, torsional

and shear deformations, and displacements of components, primarily at the yarn level. Consideration is also to be given to studies at the filament level, and to response studies on ballistic fabrics. Indirect systems, such as stress indicators, are to be included if reliable calibrations would be obtainable. The objective, of course, is to provide a guide for the selection, practical development, and interpretation of complete study systems and response analysis. These studies, in turn, would indicate developments directed to improve efficiency and reliability of critical-performance fibrous materials.

The general approach to this task in the brief period allotted was as follows: A large number of information sources were contacted or consulted (see Section 2). Our findings indicated that a certain number of candidate tracing and sensing systems might be applicable (see Section 3), and the utility of these systems was weighed in view of the immediate experimental factors to be met (see Section 4). Some of the candidate systems having use or promise for use at low or high strain rates with non-fibrous materials were estimated to be generally unfavorable if employed with the materials under consideration (see Section 5). Yet some candidate systems appeared to be favorable in part -- worthy of intensive examination or laboratory screening (see Section 6) and the potential advantages and disadvantages of several tracing and sensing systems for the materials and conditions specified have been more properly defined (see Sections 7 and 8).

2. Information Sources

To gain on-the-spot information, a questionnaire was designed and distributed to approximately 1,000 individuals or organizations. The covering letter accompanying this questionnaire outlined the salient nature of this project and its objectives. The questionnaire inquired into: a) whether present or past laboratory activities of that organization have included high strain-rate measurements or general impact tests; b) if so, which types of materials and/or structures are being/were studied; c) which strain-sensing techniques are being/have been used in this work; d) what other direct strain-sensing techniques might be applicable;

e) what indirect measurement techniques that are calibratable in strain units might be applicable; f) what literature was available concerning their own work; and g) what general literature did they recommend for attention regarding the immediate project under survey.

It is clear from the above that the questions asked were chiefly intended to permit the individual to discuss his own work, whether or not it pertained to fibrous materials. A determination was then made whether the individual's experiences could, in some way, be applicable for the immediate purposes of this project. Had direct inquiries been made concerning only tracking or sensing systems for fibrous materials in high-speed tension, it is likely that only a few replies would have been received, with little or no promise of novel experimental approaches.

Approximately 500 questionnaires were sent to research directors of the leading industrial organizations listed in Fortune Magazine. Commanding officers of approximately 100 military and governmental R & D centers were surveyed. The remaining 400 questionnaires were sent to those selected from Plas-Tech's high-speed-testing mailing list.

There were approximately 200 replies to this questionnaire, some totally negative, some giving little or no information, some providing valuable references or enclosed reports, and some donating quite stimulating, highly pertinent information.

The References and Bibliography sections at the end of this report list the articles submitted or suggested as reference material. Also included in these listings are articles which it is felt are necessary supplements for a well-rounded perspective of this general topic.

Particularly informative were Plas-Tech's "High-Speed Testing" volumes, the Journal of Experimental Mechanics, Experimental Stress Analysis, Journal of the Textile Institute, Textile Research Journal, Journal of Materials, Lyons' book "Impact Phenomena in Textiles," papers from Fabric Research Laboratory, and several works by the more prolific authors, including those of J. C. Smith.

Two computerized literature searches were made specifically for Plas-Tech on this project: a) by the Defense Documentation Center; ARB No. 076119, "Strain Sensing Systems," July 31, 1967, POR No. 190376, and b) by NASA Scientific and Technical Information Facility; "Strain Sensing Techniques," September 29, 1967, NASA Literature Search No. 5030. The summaries and references gained from these massive read-outs from the computers provided a further guide to valuable information sources.

During the four-months duration of this project, a great many scientists and engineers were personally interrogated by several of Plas-Tech's research personnel. The splendid cooperation of the several equipment manufacturers who kindly provided comprehensive brochures having excellent apparatus descriptions, specifications, and performance data is especially appreciated.

3. Candidate Tracing and Sensing Systems

Regardless of the technique for tracing and sensing (in any material, at any strain-rate level) which was gleaned from any of the information sources listed above, each was treated as a candidate for accomplishing the immediate task. It would be impracticable to give the explicit details of all candidate systems explored, and the present section of this report merely lists, by name alone, the salient varieties of tracing and sensing systems considered. These were as follows:

brittle lacquer coatings	arc voltages between points
birefringent coatings	high-speed framing photography
liquid-crystalline coatings	high-speed streak photography
bonded-wire strain gages	multiple-flash photography
bonded-foil strain gages	moiré-pattern fringes
unbonded-wire strain gages	diffraction-grating fringes
unbonded-foil strain gages	reflected interference fringes

velocity transducers	direct-contact optical extensometers
slide-wire potentiometers	direct-contact mechanical extensometers
capacitance transducers	"lock-on" optical trackers
weak-link transducers	"scan" optical trackers
reluctance transducers	accelerometers
optical tapes	Hopkins-Bar techniques
magnetic tapes	infrared detectors
radiography	fluidic approaches; microtubes
doppler radar	magnetic proximity devices

Of course, each of these salient varieties or "systems" has several specific modes of applications or cross-applications, the total number of such specific modes extending well out of sight. Clearly, it is impossible for any limited program such as this to consider in adequate detail each of the specific tracing and sensing modes of potential applicability in one, two, or more aspects of this problem. Thus the task was confined to an initial weighing of the overall merits of, not specific, but general candidate systems prior to a thorough investigation on the more promising of the specific techniques. In the following section several of the experimentally important factors are discussed which helped in the favorable or unfavorable consideration of each of the several candidate systems listed above.

4. Clarification of the Salient Experimental Problems

Most of that which is stated below has been cited before, the chief references being Lyons⁽²⁾, Butterworth and Abbott⁽³⁾, and Backer and Krizik⁽⁴⁾. A summary of the salient experimental problems with fibrous materials, especially regarding their high-speed tensing, will be given here so an

appreciation can be gained of the factors that have forced certain subsequent decisions on what are the more suitable candidate systems within the guidelines under consideration.

Firstly, it should be repeated that fibrous materials are capable of unusually high elongations, regardless of filament composition, since the individual filaments are fabricated into a nonlinear or crimped configuration and they tend to straighten-out in tension. The magnitude of the total elongation is, of course, enhanced by the use of nonbrittle filaments, such as those made of nylon (which exhibit 1 - 100% elongation, depending on its specific state of preparation or environment), or by the use of elastomeric filaments, such as those made of natural rubber (which can have 50 - 1,000% elongation).

Secondly, fibrous materials do not deform uniformly. Even if it were possible (see the "grip problem" discussed below) to apply a uniform axial tension to each yarn that is longitudinally oriented, all would not extend uniformly. The number of filaments actually experiencing an extension in each yarn that is being extended will vary from yarn to yarn. Certain yarns, even those which are longitudinally oriented, will experience a shear or a compression in longitudinally applied, macroscopic tension.

Thirdly, it is impossible to grip a fibrous material evenly. The gage-length, for example, of the filaments or yarns of a fibrous material cannot be precisely known. Knowledge of jaw-to-jaw separation, i.e., macroscopic extensibility, has no direct a priori connotation for the extensibility of a given filament or even a given yarn in the fibrous network. The grips themselves act as restraints to the normal deformation of the fibrous materials; macroscopic Poisson ratios can approach and even exceed 1.0; and, depending on the geometry of braiding, weaving, or plying, the specimen may fold, crease, ripple, or collapse during the extension.

Fourthly, for these materials, localized response will be greatly influenced by that which is attached to it as a strain-sensing device. If one pastes a gage over a given area, or if one uses a quasi-rigid lacquer over a given yarn

or interconnected yarn-section, the response of that portion of the fibrous material will usually be hypersensitively influenced by that pasting or lacquering.

Fifthly, the behavior of the heterogeneous structure of a fibrous material is influenced by internal lubrication since the microscopic mechanisms underlying macroscopic deformation are necessarily hinged on interfilament and interyarn slip.

Sixthly, if organic fibrous materials are to be considered, the role of localized factors, whether ambient temperature, internal-friction heating, interfacial-friction heating, water content, and water-vapor or organic-vapor ambients, become unusually significant influences on deformational response. Moreover, the filaments of these materials usually behave viscoelastically, not elastically.

Finally, and perhaps most importantly, concern is centered here on fibrous materials in a given mode of stressing, i.e., high-speed or impact tension. Apart from the gripping problem which makes uniformly-plane stress-wave propagation impossible, inertial attachments or even quasi-normal inertial boundaries to the fibrous material generate further sources of misleading observations. Moreover, stress waves can very readily be damped in all loosely assembled fibrous materials, and particularly if they are of viscoelastic-fiber composition.

The guidelines for this program designate macroscopic extensibilities in the 20 - 40% range which could well imply microscopic extensibilities in the 0 - 200% range if uncrimping, and folding, are also to take place. Macroscopic extensor rates up to 10,000% per second could cause severe stress redistributions and resulting microscopic strain rates that are an order of magnitude higher or lower than the macroscopic value. This problem is of particular concern with the environmentally-hypersensitive and viscoelastic, organic fibrous materials.

5. General Unfavorability of Certain Candidate Systems

Before proceeding, a definition of terms is required. The term "general unfavorability" of a certain tracing or

sensing system, as used in this report, is intended to imply that varieties of the system in question that are normally employed, or that are apparently indicated, tentatively do not appear to have sufficient merit in this particular domain of application to warrant special attention here. This term, however, is not intended to imply that the very general approach in question is totally useless in this regard, nor is it intended to imply that this approach is totally incapable of becoming extremely useful if certain of its present disadvantages become rectified with time.

Brittle lacquer coatings⁽⁵⁾ are tentatively regarded as generally unfavorable because of the probable difficulty of coating these lacquers uniformly on fibrous materials. In addition, there is the restraint which these coatings would probably impose on the microstructure of the fibrous materials, as well as the probable lack of clearly interpretative responses at the very high strain levels under consideration.

Birefringent coatings⁽⁶⁾ of the high-strain varieties that would necessarily be required here would probably still be generally unfavorable because of the difficulty of coating them uniformly on these fibrous materials. Moreover, they would contribute a finite source of restraint.

Bonded-wire and bonded-foil strain gages⁽⁷⁾ are regarded as generally unfavorable because of their low-strain levels and their difficulty or unreliability of bonding to the fibrous materials. They would also contribute a source of restraint.

Unbonded strain gage wires or foils⁽⁸⁾ of the high-strain, post-yield types (which presumably would be threaded into the fibrous matrix) might be of use in special cases but are, as a candidate system, generally unfavorable. This is due to the probable difficulty of properly integrating such wires or foils into the fibrous materials, and the necessary discrepancies between the strains of the wire or foil and the strains of the filaments or yarns. They would also be a source of restraint of a particularly erratic nature.

Velocity transducers⁽⁹⁾ (which presumably would act as sensors of strain rate or, if the output is integrated, as sensors of displacement) and potentiometers⁽¹⁰⁾ of the slide-wire or similar types are generally unfavorable because of severe inertial and restraint problems.

Weak-link transducers⁽¹¹⁾ might prove to be of help in special cases but are, as a candidate system, generally unfavorable. This results primarily from the limited information obtainable from the discontinuous strain data offered by them in structures as complex as those made from fibrous materials, without unusually elaborate assemblies and calibrations.

Reluctance transducers⁽¹²⁾ are generally unfavorable primarily because of their severe inertial and restraint contributions.

Optical or reflectance and transmittance tapes⁽¹³⁾ with subsequent photocell or photodiode sensing could be of considerable value if attachments to yarns can be made securely, without excessive restrains of the yarns, and without excessive inertial drags. However, here they will be regarded as unfavorable relative to the magnetic tapes (which are to be treated in the next two sections of this report) because they appear to have no advantages over the magnetic tapes at the high strain rates under consideration. In addition, they are considerably more expensive to make and more complex to utilize.

Doppler radar⁽¹⁴⁾ is a novel and quite promising candidate system that presumably would be employed by the application of metallic paints to the fibrous materials. This system, however, will not be further emphasized since it would require a considerable amount of developmental effort to adapt to the present application domain, and it tentatively does not appear that it would be any more informative than the presently available "scan" optical trackers, to be treated below.

Arc voltages between points⁽¹⁵⁾ would be a conceivable approach but a generally unfavorable one because of the limited information obtainable from their use and the heat,

sparking, and ozone sensitivities of the organic fibrous materials in question.

Diffraction-grating fringes⁽¹⁶⁾, as normally obtained on metals with finely spaced, straight groovings in the surface of the specimen, will be regarded as generally unfavorable until it is clarified as to how the approach can be adapted to the fibrous materials under consideration.

Reflected-light, interference fringes⁽¹⁷⁾ (perhaps facilitated by a laser-sourced, reference light beam) is an attractive approach which, however, is apparently unfavorable relative to moire' techniques (to be described in the next two sections of this report) because of the relatively limited information obtainable from the sensing of only one or two points on the specimen.

Direct-contact, optical⁽¹⁸⁾ and mechanical⁽¹⁹⁾ extensometers are generally unfavorable because of the need for contact of high-mass components with the fibrous specimens.

Accelerometers⁽²⁰⁾, of the smaller sizes available, are more favorably regarded for cordage than for webbings or fabrics since without supplementary 3-dimensional sensing of another type it would be very difficult to determine the directions of acceleration being experienced by the accelerometers mounted on the more flexible of the fibrous materials. In general, however, they are regarded as unfavorable because of this problem and other interpretational problems that probably would arise from the entire network of such accelerometers that would necessarily be required for a sufficient level of response information. Moreover, attachment problems and lead-wire restraints of, or inertial drag on, the fibrous microstructure might well prove to be formidable.

Hopkins-Bar techniques⁽²¹⁾ are generally unfavorable because of the extreme flexibility and the viscoelastic and frictional damping of the fibrous materials under consideration. Moreover, only very limited information would be obtained.

Fluidic approaches, such as the threading of microtubes containing air throughout the fibrous structures, are

generally unfavorable because of the probable difficulty of interpreting the data, difficulties of threading or attachment, and restrainments of, or inertial drag on, the fibrous microstructures.

Thus, we have tentatively labelled as "generally or relatively unfavorable" all candidate tracing and sensing systems listed in Section 3 of this report with the exception of liquid-crystalline coatings, capacitance transducers, magnetic tapes, radiography, high-speed framing and streak photography, multiple-flash photography, moire-pattern fringes, "lock-on" and "scan" optical trackers, infrared detectors, and magnetic proximity devices. These remaining systems are tentatively regarded as "more favorable," and these systems will be discussed in Sections 6 and 7 below.

6. Descriptions of the More Favorable Candidate Systems

a. Optical Trackers

There are two major varieties of highly sophisticated electro-optical extensometers on the market. One is manufactured by the Optron Corporation, Santa Barbara, California; a schematic diagram of a given model is shown in Figure 1. The other is manufactured by PhysiTech, Inc., Elkins Park, Pennsylvania; a schematic diagram of a given model is shown in Figure 2. The Optron instruments will be termed "lock-on" optical trackers and those of PhysiTech will be called "scan" optical trackers.

Both varieties of trackers have sufficiently rapid responses for the objectives under discussion, and neither requires direct contact with the specimen. Both are displacement recorders which track the motions of any object or marking that goes through a light-dark transition of sufficient contrast, such as an illuminated edge or a half-black/half-white marking.

With the earlier models of the "lock-on" trackers, the necessary source of light is emitted from the instrument itself (see Figure 1). A photocell servo system causes this spot to follow the motion of the specimen. The output presents an exact waveform of the motion. The instrument is accurately calibrated; hence displacement is read directly in inches.

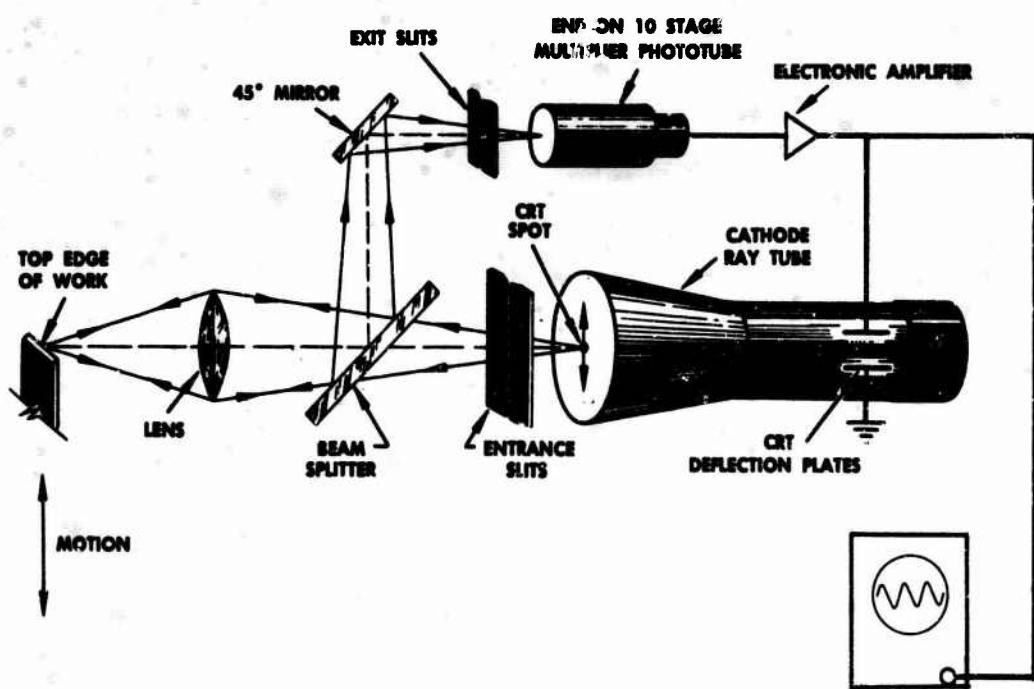


Figure 1. Schematic Drawing of a "Lock-on" Optical Tracker.
Courtesy of Optron Corporation.

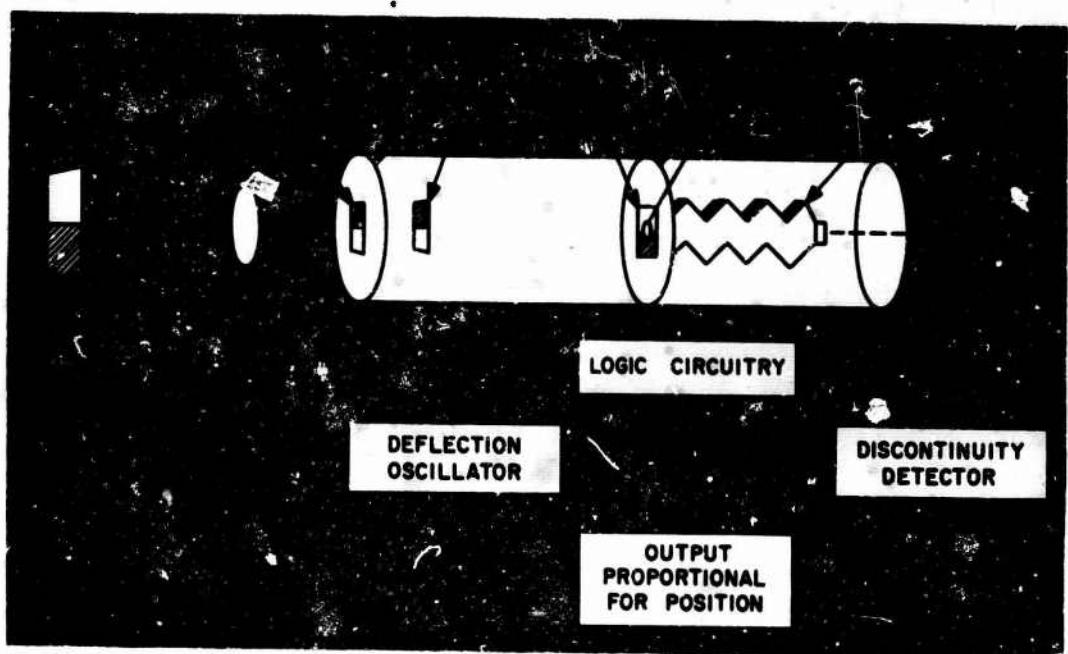


Figure 2. Schematic Drawing of a "Scan" Optical Tracker.
Courtesy of PhysiTech, Inc.

Light from the cathode-ray-tube spot passes through the beam splitter and is focused on the specimen by a lens. The servo drives the projected spot until it reaches an edge or other optical discontinuity where it locks on. This servo keeps the spot riding at the center of the discontinuity.

With later models of the "lock-on" trackers, the necessary illumination has to be supplied by the specimen itself. (This, however, provides a very remote tracking capability such as for missile or rocket take-offs).

With the earlier "lock-on" trackers, only a single optical discontinuity can be tracked at a time. For example, if detailed three-dimensional motion of the specimen is desired, three mutually perpendicular trackers are required. With later models, a single tracker (with two CRT's) is capable of two simultaneous trackings in mutually perpendicular axes.

The "scan" optical trackers (see Figure 2) also have a very remote tracking capability and depend solely on the specimen's own illumination contrast. The optical image of the area to be monitored is formed on the photocathode by an appropriate lens. Wherever light falls on the photocathode, electrons are emitted from its inner surface. Thus, an electron image is formed within the image-analyser tube. An applied electric field accelerates the electron image down the tube and focuses this image in the aperture plate. The aperture plate intercepts almost all of the image, but does pass the part of the image that coincides with the aperture. The electron multiplier located behind the aperture thus sees only that part of the image that passes through the aperture. Hence, the current output of the electron multiplier is a linear function of the intensity of a small portion of the optical image.

The deflection oscillator provides a scanning magnetic field that moves the electron image back and forth across the aperture. The discontinuity detector monitors the output of the electron multiplier and notifies the logic circuitry when the aperture translates from a light to a dark area. The logic circuitry then interrogates the deflection system as to the position of the electron image when the discontinuity was detected. This interrogated signal is then

a direct measure of the position of the optical discontinuity relative to the optic axis of the tracker. This output signal may then be applied to any conventional recording instrument to indicate position, displacement or acceleration.

This "scan" optical tracker has the unique capability of taking data on multiple simultaneous targets, or measuring discontinuities in two mutually perpendicular axes at the same time.

b. Magnetic Tapes

A "poor man's" approach to similar information suitable for displacement rates between 0.5 in./sec. and 100 ft./sec., i.e., still applicable to the immediate problem, but which does require some contact with the specimen, is the magnetic tape system. The number of simultaneous displacement rates that can be recorded with this system depends on the size of the specimen, the size of the tapes, and the number of oscilloscope channels available for the output.

This technique was developed by Krizik⁽⁴⁾ at M.I.T. The system involves the pre-recording (on a standard high fidelity magnetic tape) of a sine wave whose wave-length can be selected from tape to tape. In some of the tensile impact tests the tape is mounted on fibrous materials with one end fastened (sewed or stapled) to a point on the specimen, then run over a specially designed record-reproduce magnetic head, with the other end of the tape hanging free. When the specimen point moves, it pulls the tape with it, and the tape motion is detected at the magnetic head.

The mass of the tape used was 0.1 g./ft., and the resistance to its movement over the magnetic head was adjusted to less than 1 lb. at test speeds of 40 ft./sec. The resolution of tape reading can reach 10^{-3} in. without difficulty. The upper limit of strain reading (and displacement measurement) is sensibly infinite.

Figure 3 illustrates a computerized version* of a two-tape assembly with a direct output of strain, rather than sine waves.

* Plas-Tech Equipment Corp., Natick, Mass.

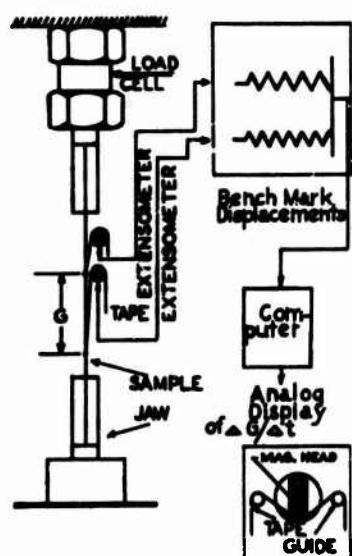


Figure 3. Schematic Drawing of a Two-tape Assembly for Application of the Magnetic Tape System to the Specimen; Automatic Strain-time Readout. Courtesy of Plas-Tech Equipment Corp.

c. Multiple-flash Photography

This is a fairly well-established procedure that does not warrant extensive description here. This system should not be confused with high-speed photography since it is done with multiple exposures on single frames of film where the moving target on the specimen in question is periodically illuminated, usually by a high- and variable-frequency stroboscope light source.

Knowing the frequency of the flashings from the stroboscope, the path and the rate of displacement of a suitable marking on the specimen can readily be traced from the multiple exposures, well within the response limits imposed by the guidelines to the present problem. This approach has been employed quite successfully with a variety of fibrous materials, principally at the National Bureau of Standards⁽²²⁾ and Fabric Research Laboratory⁽²³⁾. However, the procedure is not simple, requiring solutions of problems relating to holding the image in view, detail and depth of focus, vibrations, etc.

Several kinds of markings can be employed on a single specimen and the path and rate of motion of each kind of marking can be traced individually, even on a single film. The maximum accuracies obtainable are dependent solely on the limitations of the film, stroboscope, camera, and operational techniques employed in consideration of the rates of displacement and fields of view in question.

d. High-speed Photography

Despite the ready availability of high-speed cameras, high-speed photography is an expensive and complex art that requires considerable attention to calibration, synchronization, holding the image in view, detail and depth of focus, the exacting details of which have an intimate bearing on the final photographs and their subsequent interpretation. An excellent paper by Dunaway⁽²⁴⁾ will soon be published. It concerns applications of high-speed photography to materials testing under dynamic strain rates. The galley proofs of this paper reveal an up-to-date listing of manufacturers of several varieties of high-speed cameras.

and auxiliary equipment, and detailed descriptions of the several apparatuses and the complex techniques.

There are two major varieties of high-speed cameras available: the "framing" and "streak" types. The framing variety provides individual pictures or framed photographs, whereas the streak type provides a continuous, unframed, photograph of streaks or blurs of the target as it progresses along the film. The ultra-high-speed framing camera operates above 3×10^5 frames/sec., whereas an ultra-high-speed streak camera operates at a tracing rate greater than $3 \text{ mm.}/\mu\text{-sec.}$

High-speed and very-high-speed framing cameras are usually of the rotary-prism type, as illustrated in Figure 4. The high-speed and ultra-high-speed streak cameras are usually of the rotating-mirror type (see Figure 5).

Image-converter cameras represent the third and latest approach to high-speed and ultra-high speed photography. They are built with a special electron tube (the image-converter tube) and represent an electronic approach to high-speed photography (see Figure 6). These cameras are built by TRW Instruments, El Segundo, California, and Beckman-Whitley, San Carlos, California.

The objective lens focuses the light from the event under study on the photocathode of the image-converter tube. The electron image is then focused to cross over between the deflection plates for distortion-free image deflection and is imaged on the photoanode, where it is converted into a higher-intensity photon image and relayed to the film by an optical-lens system.

The gating grid in the image-converter tube serves as an ultra-high-speed electronic shutter allowing electrons to flow only when it is pulsed. Exposure times as short as 5×10^{-9} sec. are achievable.

These cameras are unique in yielding a light-amplitude gain between the event and the filmed image of the event. (This is opposite to the behavior of the framing and streak cameras.) However, at present there is a major drawback with image-converter cameras, due to the present

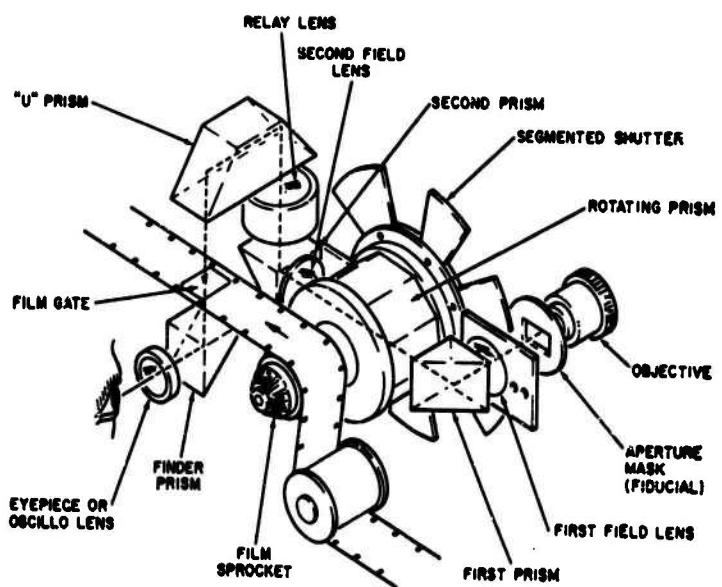


Figure 4. Internal Optical Schematic Drawing of Typical Rotary-prism Camera. Courtesy of Red Lake Labs, Inc.

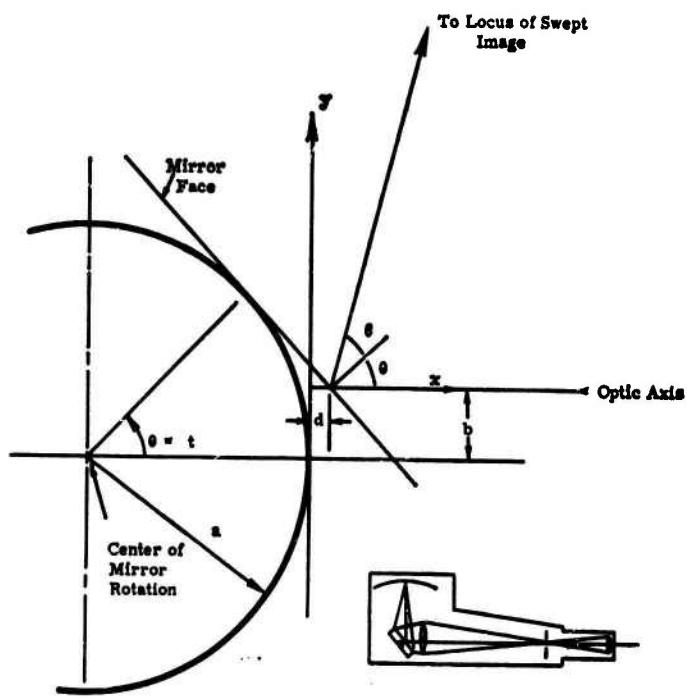


Figure 5. Internal Optical Schematic Drawing of Typical
Rotary-mirror Camera. Courtesy of Beckman &
Whitley.

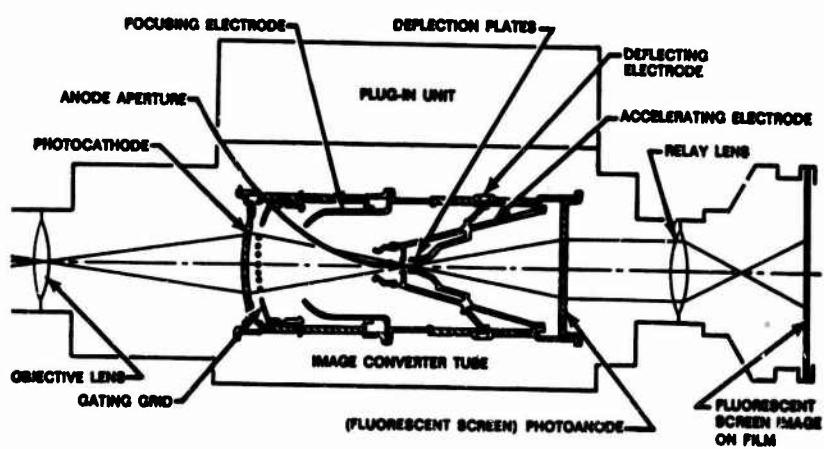


Figure 6. Internal Arrangement of Image-converter Camera. Courtesy of TRW Instruments.

availability of only five frames of 11 mm. x 25 mm. Furthermore, the resolutions obtained are not as good as standard high-speed cameras, the maximum being 16-line pairs/mm.

e. Supplementary Aids for Dynamic-photography Recordings

It is not immediately obvious what should best be photographed for a given experimental system and for a given type of data-requirement. In this subsection we will treat briefly some aids that could enhance the value of the multiple-flash or high-speed photographs.

(1) Point, Line, or Grid Photographs

This topic requires no clarification since it is obvious that a careful marking or reference-line network on the photographed specimen or in the foreground of the photographed specimen is an aid to subsequent measurements of displacement, rate of displacement, and path of displacement.

(2) Moiré Fringe Pattern Photographs

To utilize the advantage of dynamic, double-grid or double-grating fringes, it is clear that high-speed framing camera or image-converter camera photographs would be required for the purposes under consideration here. Multiple-flash and streak photographs would probably have less application in moiré fringe pattern work except for the very earliest responses of fibrous materials.

Moiré fringe-pattern techniques⁽²⁵⁾ have been widely exploited for quasi-static deformational modes, but applications to dynamic modes⁽²⁶⁾ have been only recently attempted. This approach would require a rather unique system of forming or mounting the grid or diffraction grating on the fibrous materials in question, but presumably selected areas of the specimen could be studied in this manner, perhaps at the yarn level, by miniature grating attachments with rubbery cements. As such, however, localized longitudinal strain of the yarns would not readily be measurable by the moiré technique, but localized rotational and translational modes of individual yarn motion might well be traced in this manner.

A possible approach to mounting the grating on the fibrous specimen would be to employ two gratings, both attached to the specimen, one from the top and the other from the bottom so that they can overlap most of the specimen and can be separated as the specimen is being extended. This would permit a wider range of observations than with the above mounting approach but the technique would require longitudinal guides for the loose edges of the gratings.

(3) Photographs of Colored Liquid Crystals

The suggestion for the use of the colored liquid-crystalline coatings as thermal and shear-rate sensors on fibrous materials was, to the best of our knowledge, originated by the authors of this report. Hence, some clarification of what colored liquid crystals are and how they might help in this domain of application is required and is briefly provided below.

Liquid crystals⁽²⁷⁾ are anisotropic fluids, i.e., fluids that are neither true liquids nor true solids but are in an in-between or "mesomorphic" state. Perhaps soaps are the most common examples.

All liquid crystals are birefringent, i.e., double-refracting, but some are both birefringent and optically active, i.e., they also can rotate the plane of plane-polarized light transmitted through them. These grease-like, optically active varieties are called "cholesteric" liquid crystals since the majority of them have been derived from organic-chemical modifications of cholesterol -- a material found in the human body. Apart from their birefringence and optical activity, many of the cholesteric liquid crystals are colored under ordinary light. The colors observed, however, are peculiar in appearance, actually being iridescent islands of light that appear to shift colors depending on the angle of view. In effect, they are what is called "circularly dichroic" bodies which generate their colors by transmitting one sense of circularly polarized light and selectively scattering (apparently reflecting) the opposite sense. The colors transmitted are not the same as those that are reflected.

Because the transmitted light is a different color than the reflected light, it has become a practice to spread a thin film of the cholesteric liquid crystals on an opaque, preferably black, substrate so that only the reflected colors can be seen. Further, it has been found that substrates such as Mylar or polypropylene film are best when these are blackened on their underside with a black paint.

The peculiar colors of cholesteric liquid-crystalline films that are spread on blackened plastic films are generated by the specific type of molecular packing in these anisotropic liquids. Anything that tends to disturb the delicate state of packing in these liquids will also tend to shift their colors. In the reverse sense, this also implies that colored liquid crystals can act as hypersensitive detectors of all influences to their delicate state of packing. Thus small changes in temperature or the addition of small quantities of solvents, both of which tend to dilate the liquid crystal, alter its state of packing sufficiently to produce color shifts that are readily detectable with the normal eye, but more accurately resolvable in a spectrophotometer.

Apart from altering the colors of cholesteric liquid crystals by dilating them, these colors can also be changed by rearranging their molecular packing by the application of shearing stresses. But a liquid or even a quasi-liquid cannot sustain a shearing stress unless it is being sheared at a finite rate. Thus, to shift the colors of a colored liquid crystal by shearing stresses alone, the substrate upon which it rests must experience a finite strain rate. As such, they can also be employed as strain-rate sensors.

Figure 7A shows a temperature-sensitive liquid-crystalline film (blue here, and sensibly invisible on the blackened plastic substrate). In Figure 7B, the warmth of the fingers placed behind the plastic film shifts the colors from the blue towards the red. In Figure 8A, the same kind of liquid crystal is placed over a water-based black paint applied to a nylon, Type V, MIL-C-7517 line. If Figures 8A and 8B are compared, it can be appreciated that the colors



A



B

Figure 7. A) Cholesteric liquid-crystalline film on blackened plastic film. B) Upon warming from the rear with the fingers.



A



B

Figure 8. A) Liquid crystal on blackened nylon line. B) During tensing of the specimen.



A



B

Figure 9. A) Shear-sensitive liquid crystal on plastic film. B) Color change during shearing with a glass slide.

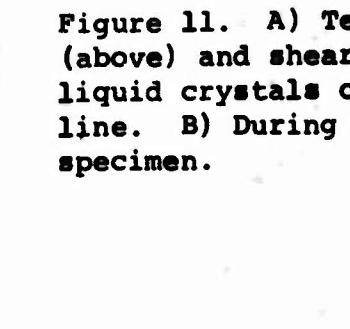


A

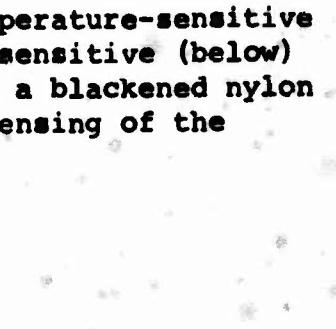


B

Figure 10. A) Shear-sensitive material on nylon line. B) During tensing of the specimen.



A



B

Figure 11. A) Temperature-sensitive (above) and shear-sensitive (below) liquid crystals on a blackened nylon line. B) During tensing of the specimen.

of the liquid crystal coatings are different. The photograph in Figure 8A was taken before the nylon line had been loaded, whereas the photograph in Figure 8B was taken during a tensile test at a low extension rate approximating 1 in/min. Because the particular liquid crystal employed in this experiment was more sensitive to temperature than it was to shear-rate, and because the level of shearing stress must have been quite low at these low shear-rates, the color shift was believed to be primarily due to temperature change. Subsequent measurements with a surface thermocouple revealed that the nylon line would have warmed-up 2°F. From static measurements on the liquid crystal itself it was found that a 2°F. rise was sufficient to alter the color of the liquid crystal from blue to light green.

Figure 9A shows a greenish liquid crystal that was intentionally made insensitive to temperature by adding a "spectrum broadener," i.e., an impurity, so that it no longer shifted its color from the green when touched with the hand. Despite this, it retained its shear-rate sensitivity, changing towards the blue when a finite shearing action was applied with a glass slide (see Figure 9B). (However, in this particular photograph the floodlight reflection from the glass slide tends to obscure the bluish hue achieved). Figures 10A and 10B show the initial and transient colors of the same liquid crystal as above prior to and during an extension of 3 in/min. Since the colors of this liquid crystal are quite insensitive to temperature, it was concluded that the observed color-shift towards the blue was due to shearing stresses acting on the liquid crystal by shear-rate contributions of both the extension and the slipping of the filaments and yarns of the nylon line.

Figures 11A and 11B show the simultaneous behavior of both temperature-sensitive (above) and shear-sensitive (below) liquid crystals prior to and during extensions of 2 in/min., respectively.

To our knowledge, the only commercial supplier of colored liquid-crystal demonstration kits is the Vari-Light Corporation, Cincinnati, Ohio. The liquid crystals described above were obtained by a combination of three of the Vari-Light materials, VL-401-R, VL-401-L, VL-401-B, with varying concentrations of specimens L-10 and L-11 obtained

from The Liquid Crystal Institute, Kent State University, Kent, Ohio, which kindly collaborated in this program. Liquid crystals can be purchased in pure forms, such as cholesteryl chloride, cholesteryl nonate, and cholesteryl benzoate, from Eastman Kodak Chemical Co., Rochester, N. Y.

The mixing of these materials to give the desired effects is very much an art at present and suitable compositions were obtained for our study only after trial and error, and re-trial mixing.

The application of colored liquid crystals, whether for sensing localized temperature changes or strain rates, offers a potential source of information on microscopic mechanisms of the deformation of fibrous materials through the detection of heating or cooling by elastic extension, internal friction, interfacial friction, and fracture, and through the detection of the rapid straining of the filaments and yarns.

(4) Photographs of Thermal Images

The photos shown in Figures 7B and 8B can be regarded as two-dimensional thermal images. It was thought during the liquid crystal studies that high-speed framing or image-converter camera photographs of the visual outputs of the more standard infrared imagers of the heat from fibrous material during tensing would be a very useful approach -- a valuable supplement to the information obtainable with colored liquid-crystalline coatings.

An interesting description of medical applications of infrared imaging devices is available⁽²⁸⁾. Figure 12 is a schematic diagram of a Barnes Thermograph, Barnes Engineering Company, Stamford, Connecticut. Another approach, Evapographs, are available from Baird-Atomic Incorporated, Cambridge, Mass., and a third, the Pyroscan, based on a photoconductive detector such as indium antimonide, is available from S. Smith & Sons, London, England. Others are available from AGA Aktiebolag, Sweden, and the General Electric Company, Schenectady, N. Y.

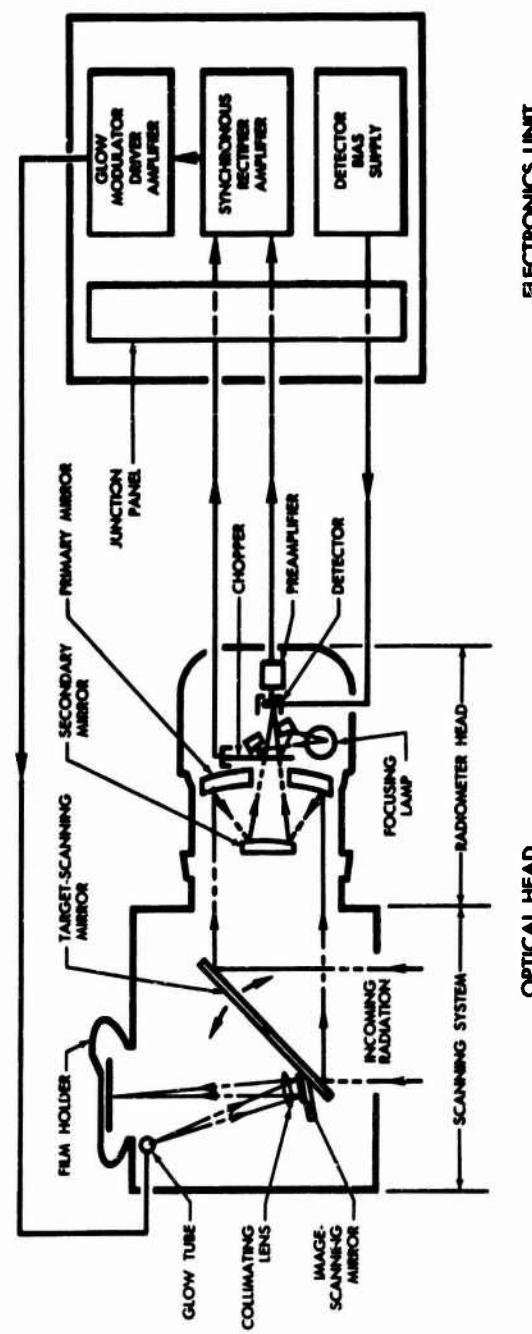


Figure 12. Schematic Drawing of the Barnes Thermograph.
Courtesy of Barnes Engineering Co.

The response-times of these units, however, are not rapid enough to meet the needs of this program. The Barnes instrument, for example, employs a thermistor detector with a large thermal lag and a mirror which slowly scans the image, requiring 4 minutes for a 12,000 in.² coverage. Photoconductive approaches are far more suitable in this regard, and lead sulfide crystals might be employed to provide 10 - 100 μ -second responses. However, much development work is required here to achieve dynamic thermal imaging of the type desired for the present objectives.

(5) Photographs of Radiation Images

High-speed radiography is a conceivable approach and is appended here for the sake of academic completeness although it is not yet clear how this would be done with organic fibrous materials whose mechanical behaviors are affected by radiation. If it is possible, then it could prove to be quite informative.

f. Capacitance Transducers

Miniature capacitance transducers of the more recent, core-in-tube type would appear to be very useful strain sensors for fibrous materials. Presumably they would be attached to individual yarns. Adequate information is not yet obtainable on their performance to permit further description here.

g. Magnetic Proximity Devices

Magnetic proximity devices have been suggested for use as strain sensors in fibrous materials and it is felt that they might prove to be quite useful. Presumably, these would consist of one or more rows of ferromagnetic pins aligned longitudinally on the fibrous specimen and their field would be sensed by a stationary magnetic core or electromagnetic coil positioned very close to the surface of the specimen. This type of device would have to be designed and analyzed for the specific application in question.

7. Discussion of the More Favorable Candidate Systems

The present-day versions of "lock-on" optical trackers do not appear to be as potentially useful for present purposes as the "scan" optical trackers since the lock-on feature necessitates that only a single source of information be followed for each electro-optical tube, whereas scanning permits several. It is clear that the fibrous material would have to be painted or dyed in most cases to provide sufficient contrast.

The magnetic tape approaches can provide a variety of useful information but are somewhat objectionable because of the need for direct attachment to the fibrous material. While this attachment could be done delicately, and while the tape's width and mass could be reduced, the approach intrinsically suffers from potential restraints of, and inertial drags on, the fibrous structure, particularly at the higher rates of extension, and particularly as the tape is being drawn through the magnetic head. Nevertheless, magnetic tapes appear to be as useful as such potential methods as magnetic-proximity devices or capacitance-transducer approaches, are readily available, and are inexpensive relative to optical-tracking procedures.

It might be anticipated that the multiflash-photography approach would not be satisfactory in axial tension tests since the successive exposures would tend to smear the important details of the fibrous structure. However, this can be avoided by traversing the camera during the successive exposures so that the successive images are oriented parallel to each other on the same film (for example, see reference No. 3). This traversal, however, has to be carefully synchronized -- an additional complication.

As mentioned in Section 6d, the image-converter camera has certain advantages over other types of high-speed cameras, such as light-amplification capability, but has relatively poor resolution and a very limited number of frames are permissible.

High-speed "streak" cameras do not appear to be as potentially useful for our present objectives as the high-

speed "framing" cameras since the details of the fibrous structure in axial tension would be lost by their streak-by action. However, they still could be useful in following the progress of properly marked features of the fibrous material.

In general, however, the high-speed framing camera appears to be the best suited of the presently available, dynamic photographic approaches for the specific problems under consideration. It is an expensive and troublesome technique, but the excellent results offered cannot, at present, be otherwise obtained. With adequate markings on the fibrous material, strain distributions and strain-rate distributions should be measurable.

The dynamic photographs of moiré-pattern fringes do not presently appear to be as immediately applicable to our present problem as was, at first, suspected. It is not clear how the specimen's grating is to be attached to the fibrous material or if such attachment is, at all, advisable. As mentioned in Section 6e, some hope for applications of the approach rests in the detection of translations and rotations of individual yarn-sections by attachments of small gratings to those localized areas by a low-modulus, presumably rubber, adhesive. Perhaps more information can be obtained by attaching two large gratings to the specimen, one from above and one from below the bulk of the specimen so that the gratings overlap. Nevertheless, the potential usefulness of the moiré techniques in analyzing the dynamic behavior of fibrous materials require extensive investigation.

The behavior of colored liquid crystals, as applied to fibrous structures, is both novel and interesting for both thermal sensing and shear-rate sensing -- highly worthy of detailed study with dynamic photography techniques. However, it cannot be presumed that the future techniques to be evolved therefrom will yield either precise data or strictly unambiguous information. Nevertheless, these coatings do things which cannot be done by other available coating techniques, and lend directly meaningful qualitative insight into the problem at hand.

Some drawbacks underlie the use of this technique, however. The colors of liquid crystals are frequently shifted on long-term exposure to atmospheric oxygen; they have a finite tendency to devitrify towards the uncolored crystalline state; they are grease-like fluids that tend to flow between the filaments and change their coating thicknesses during tensing of the fibrous material. Many of their drawbacks can be overcome, however, by a more proper compounding for the specific use under study.

The need for a black background necessitates either paint or dye applications to the fibers themselves if the fibrous material in question is not sufficiently dark. Hydrophilic paints are preferred to avoid absorption of the liquid crystal into the fibrous network. This paint, depending on its specific make-up, may or may not play a significant role in restraining the fibrous structure or altering the mechanical behavior of the fibers themselves.

It is quite clear that much work remains to be done on the liquid crystal approach, specific applications requiring specific care. There are insufficient commercial sources available for these necessary improvements to evolve spontaneously. University, research institute, or industrial contract R & D services are strongly indicated here.

If the more rapidly responding thermal imaging systems presently available could be improved, i.e., decreasing their response time, and if they could be adapted to dynamic photography procedures, this approach would provide extremely useful information concerning frictional heating from filament and yarn slips and internal-frictional heating from viscoelastic-filament deformation. Thermal energy absorption on initial elastic extension and thermal energy evolution on intermittent fatigue microfracture or final catastrophic rupture might also be revealed. Stress (hence strain) redistributions and locally selective strain-hardening processes might also be traceable by this technique. This would, of course, be a very novel approach, but sufficiently promising to be worthy of the necessary instrument development and subsequent experimentation. It tentatively appears that photoconductive approaches to thermal-imaging devices have the greatest potential for the required, rapid response.

Another potential approach is not discussed previously in this report. It would be useful to be able to detect the sounds from the stick-slip, static electricity discharge, and microfracture events occurring within the fibrous material under impact tension by a suitable assembly of high-frequency microphones. Recent discussions with Jan G. Krizik* have indicated that, knowing the sound velocity in air, three audio sensors could determine the location of the disturbance with respect to a reference coordinate system and the response might be suitably analyzed for 2-dimensional computerized readouts, i.e., dynamic sound imaging might thereby be obtained. This would appear to be a valuable device; one that is apparently worthy of detailed study and possible development.

8. Conclusions

The number of experimental tools that are suitable for analyzing the microscopic mechanisms underlying the deformation and failure of fibrous materials under tensile-impact loading is limited by the need of several performance characteristics which are dictated by the experimental circumstances to be met. The experimental tools must be applicable to a rapidly deforming and highly extensible, heterogeneous material constructed of flexible, viscoelastic filaments that may be assembled in various geometric patterns.

The rapid deformation to be experienced demands an equally rapid response from the experimental tool that is to be employed. The high extensibility of the specimen demands techniques whose reliabilities are not overly taxed by that high order of deformation. The heterogeneity of the specimen demands that the tool to be employed focus its detection capabilities on microscopic regions. The flexibility of the specimen demands that the experimental tool in question should not bias that flexibility. The viscoelasticity of the material demands that the experimental tool be sufficiently versatile to allow for time-, temperature- and vapor pressure-dependent deformational responses. The experimental condition of impact loading demands that the experimental tool act indirectly to avoid the contributions of inertia.

* Consultant, Plas-Tech Equipment Corp., Natick, Mass.

The experimental tools of chief interest here are those that permit a comprehensive perspective of the events underlying the deformation and failure of fibrous materials. Moreover, this broad perspective should not be limited to merely "seeing" the material, since "hearing" the material or appreciating its temperature distribution are equally informative. Whereas seeing a properly marked fibrous material during impact provides information on strain distributions and strain-rate distributions at the very surface of the specimen, hearing the fibrous material provides information on the locations of filament and yarn breakage, stick-slip processes in filament and yarn deformation, and static electricity discharges. Knowing the fibrous material's temperature distribution provides information on several events that include the initial cooling of the filaments on elastic extension, the slower heating of these viscoelastic filaments on inelastic deformations, the frictional heating on the slipping of filaments and yarns, and the abrupt heating on fracture of the filaments and yarns.

Experimental tools suitable for the study of mechanisms underlying the deformation and failure of non-fibrous materials at low or high strain rates are not necessarily applicable to the present problem. Section 5 of this report provides the chief reasons for not further pursuing several of the candidate tools, e.g., brittle lacquer coatings; birefringent coatings; bonded and unbonded wire or foil strain gages; velocity transducers and potentiometers; weak-link transducers; reluctance transducers; optical tapes; dopper radar; arc voltages; diffraction-grating fringes; reflected-light interference fringes; direct-contact optical and mechanical extensometers; accelerometers; Hopkins-Bar techniques; and fluidic approaches.

While not total solutions, several other approaches to the experimental problem are regarded as more favorable, e.g., optical trackers of the "lock-on" and "scan" types; magnetic tapes; capacitance transducers; magnetic proximity devices; photography of the multiflash and high-speed types; and photographic procedures employing moire fringe patterns, colored liquid-crystalline coatings, thermal imaging, and radiation imaging. These are described in Section 6 and discussed in Section 7 along with possible acoustical approaches.

Optical trackers of the "scan" type are regarded as more favorable than those of the "lock-on" type primarily because of the greater quantity of microscopic strain and strain-rate information obtainable with a single electro-optical tube during a given experiment.

Magnetic tapes, while introducing inertial and restraint problems caused by their need for attachment to fibrous materials, are easy to employ, inexpensive, and can provide much useful information concerning macroscopic and semi-microscopic strain rates. This approach appears to obviate the need to develop capacitance-transducer or magnetic-proximity-device approaches to the problem at hand.

Multiflash and high-speed-framing photography are valuable approaches to the determination of microscopic strains and strain-rates in fibrous materials under tensile-impact loading. However, high-speed framing photography is capable of better resolution in this application. These two approaches tentatively are regarded as more favorable in this application than the smeared photographs obtainable with high-speed streak photography or the yet-to-be-perfected, image-converter photography. Regardless of which photographic approach is employed, however, they all would be difficult and expensive to execute to a degree sufficient to meet the fuller needs of the present task.

Photographic approaches to recording the dynamic patterns of moiré fringes are indicated as a promising tool for future development, one that is potentially capable of providing information on microscopic axial strains, rotations, and strain-rates over the entire surface of the specimen. Their development, however, may be hampered by the need to devise novel methods of attaching suitable gratings to the specimen.

Photographic approaches to recording the dynamic colors of liquid-crystalline coatings are also indicated as a promising tool for future development, one that is potentially capable of providing information on microscopic temperature distributions and strain-rate distributions over the entire surface of the specimen. At this time, however, only the feasibility has been established (in this report) and much development work is required, as indicated in Section 7.

Photographic approaches to recording the dynamic output of thermal imaging devices are indicated as a promising tool for future development, one that is potentially capable of providing information on microscopic temperature distributions over the entire surface of the specimen. Their development, however, will depend on whether it is possible to decrease the response time greatly below that of the commercially available thermal imaging units.

Photographic approaches to recording dynamic radiation images are merely suggested as a potentiality regarding microscopic strain and strain-rate detection, and is not pursued further. Another potentiality that is only briefly suggested concerns the use of dynamic sound imaging, but it is an approach that is feasible and very promising for this application.

9. Recommendations

The following recommendations are made:

a. Attention should be given to the use of optical trackers of the "scan" type in this experimental context. Their capabilities, adaptabilities, and maximum versatilities in this context should be explored carefully.

b. Magnetic tapes should be made lighter and narrower than those now available. Drag at the magnetic head should be minimized. More suitable methods of attachment of the tape to the fibrous material should be developed. The use of 12 or more tapes in a given experiment should be attempted.

c. Multiflash and high-speed-framing photography techniques ideally need to be both refined and simplified for this application. Maximum resolution of details of the fibrous structure is desired. The specimen should be marked or gridded for precise and thorough strain-distribution and strain-rate-distribution studies. Attempts should also be made to detect rotational, shearing, and compressional modes of deformation with these exacting photographic techniques. Simultaneous photographs from three, mutually perpendicular directions would be helpful.

d. Colored liquid-crystalline coatings need to be studied and improved for suitable applicability in this experimental domain. The shear-sensitive varieties and temperature-sensitive varieties should be treated as separate entities and improved independently. Their chemical and physical stabilities, their response times, their coating-thickness requirements, their shear or temperature sensitivities, their viscosities, and their coating-application techniques all need to be studied carefully and, as needed, improved.

e. Dynamic techniques of employing moire fringe patterns in this particular application domain should be initiated and intensively studied. The use of curved grids as well as straight-line grids should be investigated. Double-exposure techniques employing single grids or alternating dark and light yarns or filaments should be tried.

f. The response times of thermal imaging devices should be greatly decreased, suitable for high-speed photographic mapping, perhaps by incorporating lead sulfide detectors with the photoconductive varieties.

g. Techniques should be developed for high-speed, two-dimensional sound mapping of fibrous materials, perhaps by the use of three high-frequency microphones associated with computerized readouts.

Our priorities of emphasis of these recommendations are as follows: 1 - f, 2 - g, 3 - d, 4 - e, 5 - c, 6 - a, 7 - b.

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13. ABSTRACT <p>A survey was made of prospective tracing and sensing systems which might be applicable to investigations of component and structural deformations within fibrous materials in response to impact tensioning. The candidate systems were generally characterized and compared as to basic suitability and probable adaptability to studies of fabrics, cords, and webbings with 20 - 40% extensibility and under extension rates up to 10,000% per second. Among the more favorably considered were those using magnetic tapes, optical trackers, capacitance transducers, magnetic proximity devices, direct multiflash and high-speed photography, and photography of moire pattern fringes, color of liquid crystals, and radiation and infrared images. Most other systems appeared either inherently, or in their present stages of development, to less well satisfy criteria of reliability, clarity of interpretation, low inertial loading, low restraint on the material, rapid response, and facility for simultaneous sensing of several key deformational factors.</p> <p>Specific recommendations are made for obtaining different evidences and perspectives of events leading up to rupture of the fibrous materials, e.g., optical mapping (high-speed framing photography), thermal mapping (dynamic infrared imaging), shear-rate mapping (dynamic imaging of colored liquid-crystal line coatings), and sound mapping (dynamic 2-dimensional acoustical analysis).</p>			

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